

**Nested Dissection for  
Sparse Nullspace Bases**

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## Abstract

We propose a nested dissection approach to finding a fundamental cycle basis in a planar graph. The cycle basis corresponds to a fundamental nullspace basis of the adjacency matrix. This problem is meant to model sparse null basis computations occurring in a variety of settings. We achieve an  $O(n^{3/2})$  bound on the nullspace basis size, and an  $O(n \log n)$  bound on the size in the special case of grid graphs.

## 1 Fundamental nullspace bases and graphs

Let  $A$  be an  $n \times m$  matrix with  $m \geq n$ , and let its rank be  $r$ . An important problem in scientific computation is to produce a basis for the nullspace of

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$A$ . In other words, we want to compute an  $m \times (m - r)$  matrix  $V$  of rank  $m - r$  such that  $AV = 0$ . The columns of  $V$  satisfy the equation  $Av = 0$ ; such a vector  $v$  is usually called a *null vector*. The nullspace problem has applications to electrical networks, optimization, and structural analysis (see Strang [1988]).

If  $A$  is sparse (as usually happens in applications), then we might hope to compute a nullspace basis  $V$  that is itself sparse. This has been a topic of recent interest in the literature; it has been addressed by Coleman and Pothén [1988], Gilbert and Heath [1987] and Plemmons and White [1990]. In general there is no reason to believe that sparsity in  $A$  implies sparsity in  $V$ : it is necessary require that  $A$  have some additional structure.

None of these earlier works are able to establish bounds on the number of nonzero entries in  $V$ . In this report we propose an algorithm that computes a nullspace basis with an asymptotic bound on the number of nonzero entries in  $V$ . In order to establish bounds, we focus attention on a simple model problem that captures the features of many real problems.

If  $V$  contains an embedded  $(m - r) \times (m - r)$  identity matrix, the basis is said to be *fundamental*. In other words, there exist permutation matrices  $P$  and  $Q$  such that

$$PVQ = \begin{pmatrix} I \\ C \end{pmatrix}.$$

Fundamental nullspace bases are especially useful in certain applications because they lead to simplified algorithms. In particular, the rows of  $V$  not in the identity matrix correspond to columns of  $A$  forming a basis of the span of  $A$ , and the null vectors give equations that express each nonbasic column of  $A$  in terms of the basis columns. In this report we focus on the fundamental nullspace basis problem.

The particular model problem we have selected is the case that  $A$  is the node-edge incidence matrix of an undirected graph. This is a matrix with  $n$  rows, one for each vertex of the graph, and  $m$  columns, one for each edge. Each column has two nonzero entries in the positions corresponding to the endpoints of the edge. These two entries are one  $+1$  and one  $-1$  in each column in arbitrary order. (In some applications, the graph is actually directed in which case the signs of the entries indicate edge orientation. However, the choice of orientation has no effect on the construction of the nullspace basis since multiplying a column by  $-1$  does not change its span.)

A nullspace basis for such a matrix has a natural combinatorial interpretation. In particular, the nonzero entries of particular column of  $V$  corresponds to a closed walk in the graph. A fundamental nullspace basis for a connected graph corresponds to the identification of a spanning tree,  $T$ , of the graph. A null vector corresponds to the unique cycle formed by edges of  $T$  in conjunction with a single edge of  $G - T$ . See Welsh [1976] for more information.

Thus, the problem of finding a fundamental nullspace basis with suitable properties is reduced to the problem of finding the right spanning tree  $T$  of  $G$ . We propose an algorithm reminiscent of nested dissection for finding this tree  $T$ . Nested dissection, a technique due to George [1973], finds a *separator* of the graph and then recursively works with subgraphs. Here, a *separator* refers to a set of nodes of a small size whose removal disconnects the graph into pieces of size at most  $2n/3$  nodes. The exact definition is contained in the next section. Unlike traditional nested dissection, which requires no further properties of the separator, we will also need the separator nodes to form a cycle.

Such separators are found in planar graphs that have a bound on the maximum face size, a result due to Miller [1986]. See the next section for the theorem.

The existence of any kind of separator automatically means that  $A$  can be partitioned in *row block angular form* (RBAF) if the rows corresponding to separator vertices are numbered last. An example of block angular form is:

$$\begin{pmatrix} B_1 & & & & & & \\ & B_2 & & & & & \\ & & B_3 & & & & \\ & & & \ddots & & & \\ & & & & & B_k & \\ S_1 & S_2 & S_3 & \cdots & S_k & S_{k+1} & \end{pmatrix}. \quad (1)$$

In this regard, our approach is most reminiscent of Plemmons and White's. They work with *column block angular form* (CBAF) and do not attempt to derive bounds on the number of nonzero entries in the basis.

It may seem that we are speaking of a very restricted class of matrices by limiting attention to node-edge adjacency matrices of planar graphs, but this is a model for the kind of matrices that occur in practice. For example,

optimization problems with flow constraints have constraint equations in the form of a graph, and the graph is typically planar or nearly planar. As another example, Pothén [1988] shows that for certain kinds of structural problems, the nullspace basis of the structural equilibrium matrix  $A$  can be entirely deduced from a cycle basis for the underlying graph.

The remainder of this paper is organized as follows. In Section 2 we give an algorithm that achieves an  $O(n^{3/2})$  bound on the size of the nullspace. An added bonus of our algorithm is that the resulting basis has structure useful for parallelism. In Section 3 we specialize our algorithm to the case of a grid graph, achieving an  $O(n \log n)$  algorithm. Finally, in Section 4 we discuss how to generalize our ideas to other kinds of matrices.

In many applications where  $A$  is not explicitly given in RBAF, we can permute rows and columns so to put  $PAQ$  in RBAF. Finding the permutation matrices  $P$  and  $Q$  that minimize the number of residual rows or columns, while producing diagonal blocks of approximately the same size, is in general a very difficult combinatorial problem to be solved exactly. See work by Stern [1990].

## 2 A tree from nested simple cycle separators

In a graph  $G = (V, E)$  with  $|V| = n$ , a set  $S \subset V$  is called an  $(\alpha, \beta)$ -separator iff:

1. Set  $S$  contains at most  $\beta\sqrt{n}$  vertices, and
2. Graph  $G - S$  has no connected component with more than  $\alpha n$  vertices.

For this section we need the following theorem from Miller [1986].

**Theorem 1** *Let  $G$  be a 2-connected planar graph with  $n$  vertices,  $m$  edges and maximal face size  $\varphi$ . Then there is an  $(\alpha, \beta)$ -SCS (simple cycle separator)  $S$ , with  $\alpha = 2/3$  and  $\beta = 2\sqrt{2\lfloor\varphi/2\rfloor}$ . Moreover,  $S$  can be found in linear time.*

Here, the term *simple cycle separator* refers to a set of vertices  $S$  that form a separator in the sense of the previous definition and that are the vertex set of a simple cycle in  $G$ .

For the remainder of this section we restrict attention to 2-connected planar graphs with face size bounded by  $\varphi$ . We remark that a strengthening of the foregoing theorem appears in Gazit and Miller [1990], that allows  $G$  to have a constant number of faces with, say,  $\sqrt{n}$  vertices without disturbing the bound.

The assumption that  $G$  is 2-connected is not actually a restriction. First, if  $G$  is disconnected, then each component can be treated separately. Second, if  $G$  is connected but not 2-connected, then the 2-connected components can be identified in linear time (see Aho, Hopcroft and Ullman [1983]). It suffices to work with 2-connected components, since any particular cycle (null vector) is contained in a unique 2-connected component of  $G$ .

Our main goal for this section is to analyze a procedure **T** that finds a spanning tree. A basic building block for **T** is Algorithm **P** that decomposes the graph using the previous theorem. The first two steps of Algorithm **P** are as follows:

**P-1:** Find in  $G$  an  $(\alpha, \beta)$ -SCS, say  $S$ .

**P-2:** Transform  $G$  into  $G'$  by contracting  $S$  into a single vertex  $\sigma$ .

These steps are illustrated in Figure 1.

**Lemma 1** *Vertex  $\sigma$  is the only articulation point of  $G'$ .*

**PROOF.** Suppose  $\tau \neq \sigma$  is an articulation point (a.p.) in  $G'$ . Let  $G'_1, G'_2, \dots, G'_k$  be two of the 2-connected components of  $G'$  articulated by  $\sigma$ . Since  $\sigma$  is an a.p. in  $G'$ ,  $\tau$  belongs to exactly one  $G'_i$ , say  $G'_1$ . Let  $G'_{1,1}, G'_{1,2}$  be two of the 2-connected components of  $G'_1$  articulated by  $\tau$ . Since  $\tau$  is an a.p.,  $\sigma$  belongs to exactly one  $G'_{1,i}$ , say  $G'_{1,1}$ .

Now  $G'_{1,2}$  is a subgraph of  $G$ , because it has not affected by the contraction of  $S$ . But then  $\tau$  is an articulation point in  $G$  between  $G'_{1,2}$  and  $S$ , which contradicts the hypothesis that  $G$  is 2-connected. ■

By virtue of Lemma 1 we can define the final step of procedure **P**:

**P-3:** Separate the 2-connected components of  $G'$  into disconnected subgraphs,  $G_1^1, G_2^1, \dots, G_k^1$  with every subgraph receiving its own copy of  $\sigma$ , the articulation point in  $G'$ . The final graph,  $G^1$ , is the disjoint union of the subgraphs  $G_i^1$ . (Figure 2.)

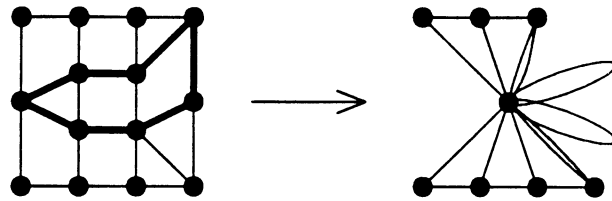


Figure 1: Contracting a cycle to a single node.

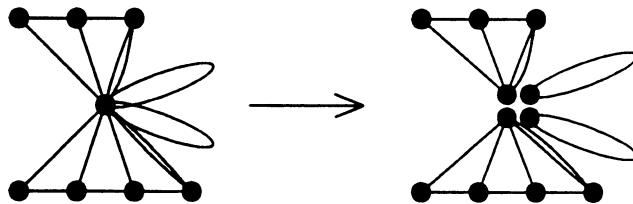


Figure 2: Graph  $G_1$  based on Figure 1.

**Lemma 2** *The maximal face size of  $G_i^1$ , a connected subgraph of  $G^1$ , does not exceed the maximal face size of the original graph  $G$ .*

PROOF. Observe that, given an embedding of  $G$ , there is an embedding of  $G_i^1$  that corresponds to topologically contracting the embedded edges of  $S$ . Focus on this embedding of  $G_i^1$ .

Let  $v_1, v_2, \dots, v_l$  be the vertices in a face of  $G_i^1$ . If  $v_k \neq \sigma$  for  $k = 1, \dots, l$ , then the face was not changed by the contraction of  $S$ , and the lemma follows. Now say  $v_l = \sigma$ . The list of vertices  $v_1, \dots, v_l$  in the embedding of  $G_i^1$  have no edges adjacent to them in the interior of the face. Since no edge adjacent to these vertices was deleted by the contraction process, this means that vertices  $v_1, \dots, v_{l-1}$  form a path in  $G$  such that there are no edges adjacent to these vertices that are embedded on one "side" (either left or right) of the path. Thus, this path is part of a face in  $G$  of size at least  $l$ . ■

By virtue of Lemma 2 we can recursively apply procedure **P** to each of the connected subgraphs in  $G^1$ . That will be the basis for procedure **T** to construct the spanning tree. The parameter  $\kappa$  below is a constant depending on  $\varphi$  that we will specify later.

If  $|V(G)| \leq \kappa$

**T-1:** Return an arbitrary spanning tree  $T$  in  $G$ .

Else

**T-2:** Apply procedure **P** to  $G$  (using the SCS  $S$ ).

In each subgraph  $G_i^1$ , recursively use procedure **T** to get a tree  $T_i$ .

**T-3:** Construct in  $G$  the spanning tree  $T$ , joining:

- (a) Forests  $\hat{T}_i$ , the uncontracted versions of  $T_i$ , and
- (b) The SCS  $S$  with an arbitrary edge deleted.

This procedure is illustrated in Figure 3 for the graph used in Figure 1 and Figure 2

**Lemma 3** *The graph returned by procedure **T** is a spanning tree.*

PROOF. We will prove the theorem by induction on the number of levels we recursively called procedure **T**. At the last recursive call **T-1** returns a



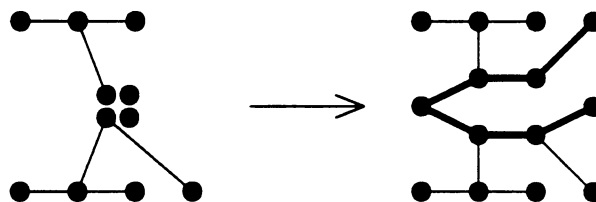


Figure 3: Finding a tree recursively.

spanning tree. This is the basis for our inductive argument. Now assume that the recursive calls to  $T$  return spanning trees  $T_i$  at each subgraph  $G_i^1$ . To complete our induction we have to prove that  $T$  is a spanning tree for  $G$ .

Let  $C$  be cycle  $S$  with an arbitrary edge deleted, so that  $C$  is a simple path spanning the vertices of  $S$ . We argue by contradiction that  $T$  cannot have cycles. Suppose  $T$  has a cycle. Since each  $\hat{T}_i$  is a forest and the various  $\hat{T}_i$ 's have no common vertices, the cycle must be formed by edges of  $C$  and a particular  $\hat{T}_i$ . But this is not possible because then the same cycle could be contracted to form a cycle in  $T_i$ .

Also, we claim  $T$  is connected. This is because the forests  $\hat{T}_i$  and  $C$  span all the vertices, and each tree in the forest made up of  $\hat{T}_i$ 's contains a vertex of  $C$ . ■

We have now demonstrated that procedure  $T$  constructs a spanning tree. We now put an upper bound on the length of the cycle formed by adding any edge of  $G - T$  to  $T$ . We use the term *co-tree edge* to refer to such edges, and the term *co-tree cycle* to refer to the unique cycle induced by a co-tree edge. The co-tree cycles correspond to the null vectors in the basis,

and the number of edges in the co-tree cycles correspond to the number of nonzero entries of the nullspace basis.

**Theorem 2** *A co-tree cycle of  $T$  has length at most  $\delta\sqrt{n} + \kappa$ , where  $\delta = \beta / (1 - \sqrt{\alpha + 1/\kappa})$ .*

PROOF. Let  $f(n)$  be the maximum number of edges in a co-tree cycle. We will prove the theorem by induction on the number of levels we recursively called procedure **T**.

If  $n \leq \kappa$ , the theorem is trivial.

Otherwise, let  $S$  denote the SCS constructed at the top level of **T**, and observe that a co-tree cycle must lie interior to one of the subgraphs  $G_i^1$ , plus  $S$ . Now we can use Theorem 1 to get the recursion:

$$f(n) \leq f(\alpha n + 1) + \beta\sqrt{n}.$$

The first term accounts for the edges in  $G_i^1$ , a graph that has at most  $\alpha n$  vertices plus the copy of  $\sigma$ , and the second term accounts for the edges in  $S$ . Our induction hypothesis states that

$$f(\alpha n + 1) \leq \delta\sqrt{\alpha n + 1} + \kappa.$$

So to prove our theorem it suffices to establish, for all  $\kappa \leq m \leq n$ , that

$$\delta\sqrt{\alpha m + 1} + \beta\sqrt{m} \leq \delta\sqrt{m}$$

i.e.,

$$\delta \geq \beta / \left(1 - \sqrt{\alpha + 1/m}\right).$$

Since  $\alpha = 2/3 < 1$ , we can choose  $\kappa = 30$  to ensure that the last denominator is positive, and given  $\kappa$  and  $\beta$  we can choose  $\delta$  to satisfy the inequality for  $m = \kappa$ . For example, if the graph is triangulated, then Theorem 1 gives us  $\beta = \sqrt{8}$ , and taking  $\kappa = 30$  we can take  $\delta = 20$ . ■

As a corollary to Theorem 2, we can easily put a bound on  $g(n)$ , the total length of the all co-tree cycles, i.e., the number of nonzeros in the nullspace basis. Theorem 2 give us a bound for  $f(n)$ , the length of the longest co-tree cycle. A planar graph with  $n$  vertices has at most  $3n - 6$

edges (Harary [1972]). Thus, there are at most  $(3n - 6) - (n - 1)$  co-tree cycles, so the total co-tree length,  $g(n)$  is bounded by  $(2n - 5)f(n)$ , i.e.,  $O(n\sqrt{n})$ .

Finally, let  $T$  be the tree in  $G$  constructed by algorithm T. Now we can see that the incidence matrix of the cycles in the cycle basis can be written in RBAF. In particular, we number the edges of  $G$  according the 2-connected components of  $G'$ , with the edges of  $S$  numbered last. Then each cycle in the nullspace basis has nonzeros in rows of  $V$  corresponding to edges of one particular 2-connected component, plus edges from  $S$ . We can also nest the RBAF structure in  $V$  according to the recursive levels of procedure T.

### 3 The grid graph

For the  $(k - 1) \times (k - 1)$  grid graph  $G(k)$ , with  $n = (k - 1)^2$  vertices and  $m = (k - 1)(k - 2)$  edges, we can define a spanning tree  $T(k)$  that gives us a better bound on the total length of the co-tree cycle basis.

For this section we only consider the case that  $k = 2^j$ , although our results can be generalized. The  $k = 16$  graph is illustrated in Figure 4.

Tree  $T(k)$  is constructed recursively. In the case that  $k = 2$ , i.e., a  $1 \times 1$  grid graph, the spanning tree is the unique node of the graph. This is the basis of the recursion. In order to construct  $T(k)$  for  $k > 2$ , we need the following basic building blocks:

$\alpha(k)$  : The central vertex of  $G(k)$ , i.e., the vertex at position  $(k/2, k/2)$ .

$\beta(k)$  : The vertex of  $G(k)$  at position  $(k/2, k/4)$ .

$\gamma(k)$  : The vertex of  $G(k)$  at position  $(k/2, 3k/4)$ .

$X(k)$  : The edges of  $G(k)$  of the central row or column.

$H(k)$  : The edges in  $X(k)$  plus the edges incident to  $\beta(k)$  or  $\gamma(k)$ .

Graph  $H(k)$  is illustrated in Figure 5; vertices  $\beta(k)$  and  $\gamma(k)$  are shown as squares, and vertex  $\alpha(k)$  is shown as a bullseye.

Notice that  $G(k) - X(k)$  has four connected components, each of which is isomorphic to  $G(k/2)$ . We can recursively define  $T(k)$  as  $H(k)$  plus a copy

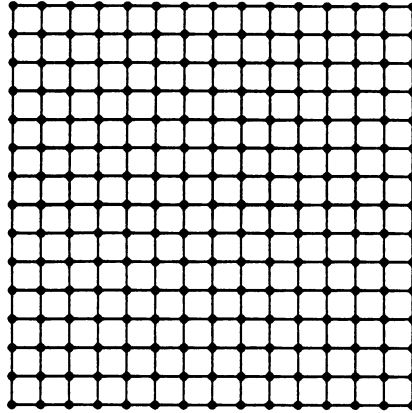


Figure 4: The grid graph in the  $k = 16$  case.

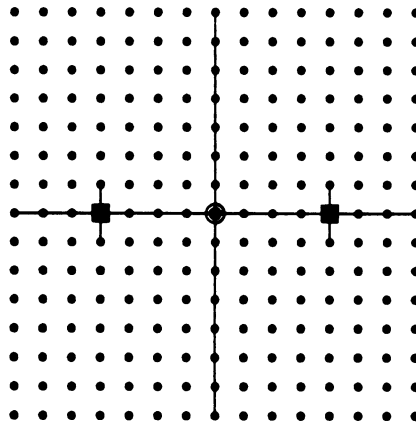


Figure 5: The graph  $H(k)$ , with  $\alpha(k), \beta(k), \gamma(k)$  illustrated.

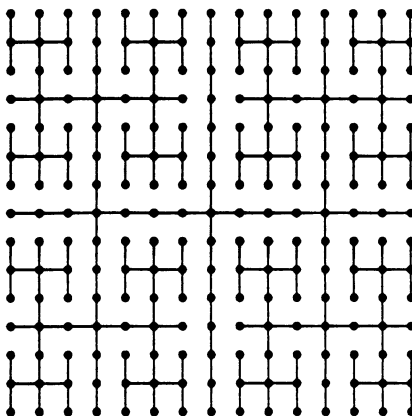


Figure 6: The graph  $T(k)$  in the case  $k = 16$ .

of  $T(k/2)$  for each component. We omit the proof that  $T(k)$  is indeed a spanning tree of  $G(k)$ . An example of  $T(k)$  in the case  $k = 16$  is illustrated in Figure 6. This tree is similar to a graph that has occurred in the VLSI literature known as the H-tree (see Ullman [1984]).

We consider the tree  $T(k)$  to be rooted at  $\alpha(k)$ , and define  $d^k(\omega)$  as the distance of a vertex  $\omega$  in  $T(k)$  to the root, ie  $d(\omega, \alpha(k))$ . We denote by  $r(k)$  the radius of  $T(k)$ , i.e., the maximal distance  $d^k(\omega)$ .

**Lemma 4** *The radius  $r(k)$  of  $T(k)$  is bounded by  $k$ .*

**PROOF.** Recall  $k = 2^j$ . We will prove the lemma by induction on  $j$ . If  $j = 1$ , then  $T(2) = H(2) = \alpha$  and  $r(2) = 0$ . This is the basis for our induction.

For  $k > 1$  let us consider  $d^k(\omega)$  for an arbitrary vertex  $\omega \in T(k)$ . If  $\omega \in X(k)$  then  $d^k(\omega) \leq k/2$ , because each of the four branches of  $X(k)$  has diameter  $k/2$ . If  $\omega \notin X(k)$ , then  $\omega$  belongs to one of the four copies of  $T(k/2)$  rooted at  $\alpha(k/2)$ , and connected to  $H(k)$  through  $\beta(k)$  or  $\gamma(k)$ . Let us say that it is in the upper left copy of  $T(k/2)$ , so that it is rooted through  $\beta(k)$ . Let  $\alpha(k/2)$  denote the root of the particular copy of  $T(k/2)$

under consideration. Then we have the chain of equations:

$$\begin{aligned}
d^k(\omega) &= d(\omega, \alpha(k)) \\
&= d(\omega, \alpha(k/2)) + d(\alpha(k/2), \alpha(k)) \\
&= d^{k/2}(\omega) + d(\alpha(k/2), \beta(k)) + d(\beta(k), \alpha(k)) \\
&= d^{k/2}(\omega) + k/4 + k/4 \\
&\leq r(k/2) + k/2.
\end{aligned}$$

Hence  $r(k) \leq r(k/2) + k/2$ , and that gives the induction step for our hypothesis,  $r(k) \leq k$ . ■

**Theorem 3** *The total length  $g(k)$  of the co-tree cycle basis for the tree  $T(k)$  in the  $(k-1) \times (k-1)$  square grid  $G(k)$  is asymptotically bounded by  $6k^2 \log k$ .*

PROOF. Let us first look at the co-tree cycles that have edges in  $X(k)$ . We observe that the only co-tree cycles with edges in  $X(k)$  are those generated by co-tree edges incident to vertices of  $X(k)$ . Also there are only  $4k$  of those edges. Let  $f(k)$  be length of a given co-tree cycle,  $S$ , intersecting  $X(k)$ . Observe that the edges of  $S$  not in  $X(k)$  must lie in one of the four copies of  $T(k/2)$ . The number of such edges, as in the previous lemma, is at most  $r(k/2) + k/4$ . The number of edges of  $S$  in  $X(k)$  is at most  $3k/4$ , because they must be in the border of one of the quadrant regions, and can not cross  $\beta(k)$ . Therefore, the total number of edges in  $S$  is bounded as follows:

$$f(k) \leq (r(k/2) + k/4) + 3k/4 \leq 3k/2.$$

Now, all the remaining co-tree cycles lie in one of the copies of  $T(k/2)$ , and we can write

$$g(k) \leq 4g(k/2) + (4k)f(k) \leq 4g(k/2) + 6k^2.$$

But a recursion in the form  $g(k) \leq 4g(k/2) + ck^2$  is known to be bounded by  $ck^2 \log(k) + O(k^2)$ . Indeed, George's original [1973] derivation of nested dissection on grids came up with the same expression for the fill during Gaussian elimination. So we can limit the total length of the  $T(k)$  co-tree cycle basis for  $G(k)$  by:

$$g(k) \leq 6k^2 \log k + O(k^2) = 6n \log n + O(n).$$

■

## 4 Generalizing the construction

In this section we discuss how to generalize the results of Section 2 to matrices other than adjacency matrices of planar graphs. We first note that the planarity assumption was necessary only to obtain simple cycle separators. We see that the necessary property of the separator was not that it was a simple cycle, but rather that the subgraph induced by the separator nodes was connected. Indeed, the separators in Section 3 were not cycles. With this weaker hypothesis all of the results of Section 2 go through. Recent results by Miller, Teng and Vavasis [1990] suggest that very broad classes of graphs could have connected separators.

If we want to generalize beyond adjacency matrices of graphs, we see that the first crucial property in our analysis was that matrix  $A$  can be written in the form of (1). This is not enough to carry out our algorithm; this form is analogous to a graph  $G$  having a node separator but not necessarily a connected node separator. The generalization of the “connected” property is that matrix  $S_{k+1}$  has full row rank. If this happens, then it can be shown using linear algebra that it suffices to find a nullspace basis for  $S_{k+1}$  and for  $\hat{B}_1, \dots, \hat{B}_k$ , where  $\hat{B}_i$  denotes the matrix

$$\begin{pmatrix} B_i \\ w_i^T \end{pmatrix}.$$

In this formulation  $w_i^T$  is a row vector with a “don’t care” entry for each column in which  $S_i$  has at least one nonzero entry. From fundamental nullspace bases for  $\hat{B}_i$  and for  $S_i$  we can assemble a fundamental nullspace basis for  $A$ . This construction works only under the usual noncancellation assumption that the nullspace basis of  $A$  can be predicted entirely from the positions of the nonzero entries in  $A$ . See, for example, Pothen [1984].

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